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13. ABSTRACT *(Maximum 200 words)*

Design of meso-scale energy systems, either for power production or heating/cooling, will require understanding of the thermodynamics of the proposed system as well as knowledge of the heat transfer and fluid dynamic characteristics associated with flow in microchannels. These proposed thermal energy systems require the exchange of significant amounts of heat and most take advantage of the large heat transfer rates accompanying phase change. Evaporators and condensers for meso-scale energy systems will most likely be constructed of microchannels due to the microfabrication constraints that limit most structures to two-dimensional planar geometries. Thus, forced convection boiling and condensation in horizontal microchannels will provide the mechanisms for heat exchange. Unfortunately, little is known about these two processes in microchannels. No work on condensation in microchannels has yet to be reported. For single-phase and phase-change heat transfer processes, knowledge of the heat transfer rates and pressure drops in microchannels is vitally important for the future design of complete meso-scale energy systems. Thus, design tools, such as analytical and numerical models and experimental correlations, that account for microscale effects must be available to engineers as they consider complete system design. This report summarizes the first steps taken to assess convection heat transfer in horizontal microchannels.

14. SUBJECT TERMS

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1. Forward

Design of meso-scale energy systems, either for power production or heating/cooling, will require understanding of the thermodynamics of the proposed system as well as knowledge of the heat transfer and fluid dynamic characteristics associated with flow in microchannels. Three types of convective processes are of interest: single phase, convective flow boiling, and condensation. These proposed thermal energy systems require the exchange of significant amounts of heat and most take advantage of the large heat transfer rates accompanying phase change. Evaporators and condensers for meso-scale energy systems will most likely be constructed of microchannels due to the microfabrication constraints that limit most structures to two-dimensional planar geometries. Thus, forced convection boiling and condensation in horizontal microchannels will provide the mechanisms for heat exchange. Unfortunately, little is known about these two processes in microchannels. No work on condensation in microchannels has yet to be reported. For single-phase and phase-change heat transfer processes, knowledge of the heat transfer rates and pressure drops in microchannels is vitally important for the future design of complete meso-scale energy systems. Thus, design tools, such as analytical and numerical models and experimental correlations, that account for microscale effects must be available to engineers as they consider complete system design. This report summarizes the first steps taken to assess convection heat transfer in horizontal microchannels.

2. Table of Contents

3. List of Appendixes, Illustrations, and Tables

A list of Appendixes, Illustrations, and Tables is not necessary and is therefore not provided.

4. Statement of the Problem Studied

Proposed Study Details

It was proposed to study condensation in microchannels for the purpose of creating some of the design tools that are required for the effective design of meso-scale energy systems, either for power production or heating/cooling. Knowledge of the thermodynamics of any proposed system as well as knowledge of the heat transfer and fluid dynamic characteristics associated with flow in microchannels is desirable. The details of the proposed study are listed below.

1. A universal flow apparatus (UFA) designed for the experimental study of fluid and heat transfer phenomena in microgeometries down to approximately 10 μm will be used in the study.

2. Data acquisition will be computer controlled.

3. Temperature measurement will be made using fine-gage thermocouples.

4. Microchannels are the preferred type of conduit for the experiments. Several possible technologies are proposed for microchannel fabrication including, micro milling, laser ablation, and surface micromachining.

5. Commercially available microtubes are also suggested for inclusion in the study.

6. The hydraulic diameter for the microchannels and microtubes is to range from 50 μm to 1 mm.

7. Refrigerants, such as R134a, are suggested for the heat transfer fluid.

8. A saturated vapor or a slightly superheated vapor is to be introduced into the microchannel. The fluid quality at the outlet should be in the range from 0.1 to 0.9.

9. Cooling is to be supplied by a chilled water jacket surrounding the microchannel(s). An energy balance performed on the microchannel and surrounding water jacket will provide the necessary data to determine the desired performance parameters.

10. The experiment will provide average values of Nusselt number and pressure drop (friction factor).

Changes to the Proposed Study

The single biggest change to the original plan was the design and use of an open-system system operating in batch mode for the flow loop. The advantages to this type of system include

(1) ease of fabrication, (2) inexpensive parts, (3) shortened construction time, (4) simple data acquisition, and (5) uncomplicated process control. However, since the system was open, refrigerants could not be used. Other proposed details were changed as a result of the decision to use an open-cycle system. Referring to the ten (10) items given immediately above, the changes made to the proposed experimental study follow and are denoted by a star (*).

1.* The universal flow apparatus is still under development. An open-cycle batch process system was used for the flow of the test fluid in the study.

2.* Data acquisition was accomplished using a combination of digital and analog instrumentation. The process was not computer controlled.

3. Temperature measurements were made using fine-gage thermocouples.

4.* Microchannels were not used in the study.

5. Stainless steel microtubes were purchased and used for the flow conduits.

6. The inner diameter of the microtubes purchased ranged from 50 to 500 μm. Only the 250 μm i.d. microtube was evaluated for condensation heat transfer.

7.* Refrigerants were eliminated as condensation fluids since an open-cycle system was used.

8. The conditions of the working fluid at the inlet and outlet of the test section remained within the proposed ranges.

9. Heat transfer for the condensation process was provided by a cooling water jacket. An energy balance on the test section provided the necessary data for parameter evaluation.

10. Nusselt number and pressure drop data (friction factor) were determined for the microtube over a fairly wide range of inlet conditions (i.e., quality, temperature, flow rate, and Reynolds number).

Future Work

Work is continuing on the study of condensation in microgeometries at the University of Utah. The ongoing work is funded by the Department of Mechanical Engineering, primarily by supporting students through Teaching Assistantship positions. There are two primary thrust areas for the current work that evolved from the work related in the Technical Report "Forced Convection Condensation of Steam inside a Horizontal Microtube".

The use of thermocouples for temperature measurement in microsystems leads to a number of problems since the thermocouple wires are sometimes larger than the systems under study. The fine-gage wire is difficult to work with and breaks easily. Attachment of the thermocouples to the surface of interest requires great care so that the adhesive does not provide undue thermal insulation. Insertion of thermocouples into surfaces may not be possible since the surface may be too thin to drill. Quite frequently, the inside surface temperature is desired in an internal heat transfer experiment. The placement of thermocouples to measure inside surface temperature in a

microtube is a very difficult task. Because of these difficulties in temperature measurement, alternative methods are being developed that will provide the desired heat transfer data from heat transfer experiment without the need for interior surface temperature measurement. Work is nearly complete on a method that uses a genetic algorithm to determine the Nusselt number assuming a relationship of the form

$$Nu_{D,t} = C\,\mathrm{Re}_D^m\,\mathrm{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)_t^{0.11} \quad (1)$$

where $Nu_{D,t}$ = Nusselt number based on diameter on the tube side
Re_D = Reynolds number based on tube diameter
Pr = Prandtl number
μ = viscosity
μ_w = viscosity of the fluid at the wall temperature

The experimental apparatus for the general heat transfer experiment consists of a double-pipe heat exchanger with the inside tube representing the surface where the heat transfer coefficient is desired. The data required for the analysis are the flow rates of the two fluids and the inlet and outlet temperatures of the two fluids. The genetic algorithm method is an improvement on the Wilson Plot method [1] used frequently in heat transfer experiments. The disadvantages of the Wilson Plot method include (1) the Reynolds number and Prandtl number for the water flow in the annulus must be held constant, (2) the outlet temperature of the annulus fluid must be held constant, and (3) the values obtained for the desired constants (C, m, and a third constant not given in Eq. 1) are dependent upon the iteration step size which limits the accuracy of the method. All of these deficiencies will be remedied by the newly developed data reduction method.

Work is continuing on a universal flow apparatus (UFA) designed for the experimental study of fluid and heat transfer phenomena in microgeometries down to approximately 10 µm. When completed, the UFA will consist of micro pumps, several flow meters with a wide range of flow rate capability, pressure transducers, heat exchangers, flow regulation devices, and fluid reservoirs. All of this equipment will be installed on a vibration isolation table to eliminate external vibration sources that may affect the fluid flow. A versatile fixture, which may be easily integrated into the UFA, will be designed and constructed so that it may accommodate a variety of microchannel configurations. The fixture will also include external cooling sources to provide the required heat fluxes. Data acquisition will be accomplished by a computer controlled system.

With the completion of the data reduction method and the UFA, further experiments will be conducted on condensation in microtubes. As a results of these improvements, data will have improved uncertainty and a wider range of Reynolds number will be possible (a narrow Reynolds number range made it impossible to detect correlation between condensation Nusselt number and the Reynolds number in the current study). Future technical reports will report on the genetic algorithm data reduction method and the experimental results from the UFA.

5. Summary of the Most Important Results

All of the results are given in the Technical Report " Forced Convection Condensation of Steam inside a Horizontal Microtube". The important results and conclusions follow.

a. The inside diameter of the microtube used in the experiments is the smallest ever used in similar condensation experiments.

b. The average Nusselt number determined experimentally for the condensation process showed significant deviation from the values reported in the literature for large-scale conduits. The microtube average Nusselt number data were 3 to 50 times smaller than similar macrotube data.

c. The average Nusselt number data were not dependent on the inlet saturated vapor Reynolds number or inlet saturated vapor velocity.

d. The average Nusselt number data were found to be only correlated with the change of vapor quality across the microtube.

e. The deviation of Nusselt number behavior from previously reported large scale data was thought to be most affected by the condensation droplet size relative to the interior dimensions of the microtube.

f. The Reynolds number range was limited to approximately one order of magnitude due to limitations in flow rate measurement. This range, however, represents the anticipated Reynolds number range for proposed meso-scale/microscale thermal fluid systems. Systems will most likely not be operated at high Reynolds numbers due to the extreme pressure drop penalty associated with the small tube diameters.

g. The narrow experimental Reynolds number range prevented any correlation of the Nusselt number with the Reynolds number. Correlations of Nusselt number with Reynolds number for large-scale pipes in the literature [2, 3] are based on Reynolds number ranges that are several orders of magnitude in size.

6. List of All Publications and Technical Reports

Publications - none

Technical Reports

1. Forced Convection Condensation of Steam inside a Horizontal Microtube

7. List of All Participating Scientific Personnel

Personnel	Title	Funding Period	Degree Earned
Tim Ameel	Principal Investigator	3/16/98 – 3/14/98	NA
Alex Monti	MS Grad Student	3/16/98 – 3/14/98	MS (expected May, 2000)
Shiping Yu	MS Grad Student	3/16/98 – 3/14/98	MS (December, 1999)

8. Report of Inventions

No inventions for this reporting period.

9. Bibliography

[1] Ferrell, P., Wert, K., and Webb, R.L., 1991, Heat Transfer and Friction Characteristics of Turbulent Radiator Tubes, *SAE Transactions*, Vol. 100, Section 5, pp. 218-230.

[2] Akers, W.W., and Rosson, H.F., 1960, Condensation Inside a Horizontal Tube, *Chemical Engineering Progress Symposium Series*, Vol. 56, No. 30, pp. 145-149.

[3] Akers, W.W., Deans, H.A., and Crosser, O.K., 1959, Condensing Heat Transfer Within Horizontal Tubes, *Chemical Engineering Progress Symposium Series*, Vol. 55, No. 29, pp. 171-176.

10. Appendices

No appendices are provided with this report.